SIM technology development overview—light at the end of the tunnel

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ABSTRACT

Optical and infrared interferometry will open new vistas for astronomy over the next decade. Space based interferometers, operating unfettered by the Earth's atmosphere, will offer the greatest scientific payoff. They also present the greatest technological challenge: laser metrology systems must perform with sub-nanometer precision; mechanical vibrations must be controlled to nanometers requiring orders of magnitude disturbance rejection; a multitude of actuators and sensors must operate flawlessly and in concert. The Jet Propulsion Laboratory along with its industry partners, Lockheed Martin and TRW, are addressing these challenges with a development program that plans to establish technology readiness for the Space Interferometry Mission by end of 2004.

Keywords: interferometry, metrology, pointing, control, nanometer, picometer, optics, lasers

1. INTRODUCTION

The Space Interferometry Mission (SIM), with a target launch date of December 2009, will be one of the premiere missions in the Astronomical Search for Origins (ASO) Program, NASA's bold endeavor to understand the origins of the galaxies, of planetary systems around distant stars, and perhaps the origins of life itself. SIM's niche in the Origins Program is to detect planets around stars in our neighborhood of the Milky Way galaxy. SIM aims to find solar systems like our own and will be sensitive enough to identify Earth-like planets in these solar systems. This adventure of discovery will be enabled by an explosive growth of innovative technology, as exciting in its own right as the underlying scientific quest.

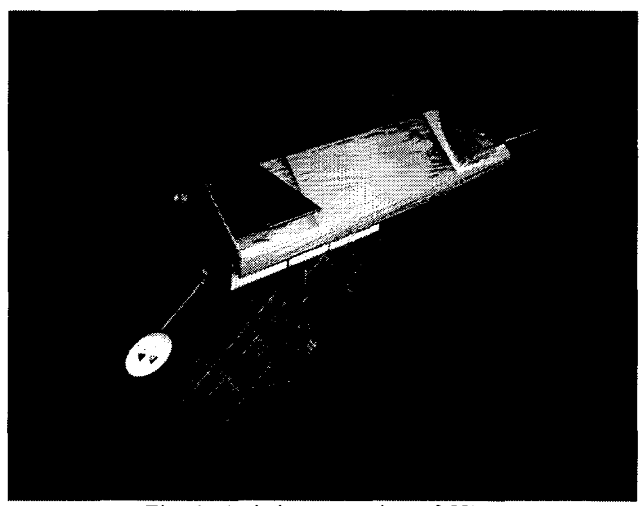
Fig. 1: Artistic conception of SIM.

SIM (see Fig. 1) drives the state-of-the-art in optomechanical and optoelectronic systems as well as presenting daunting challenges in precise stabilization of lightweight deployable structures and coordinated computer control of numerous optical surfaces. In this sense it very much embodies the principles of the Origins program—to couple breakthrough science with breakthrough technology in the service of both a fuller knowledge of our universe and a richer technological landscape that helps preserve our nation's preeminence as a force for global innovation. In this regard technology has become an important end-in-itself for NASA's Origins missions.

Fig. 2 shows the layout of the SIM instrument, which occupies most of the volume within the flight system depicted in Fig. 1. The instrument consists of four individual optical interferometers whose baselines are parallel. Each baseline is approximately 10 meters long, implying that SIM will be a large payload filling the entire Space Shuttle bay, should it be launched on the Shuttle, or a large shroud of an expendable launch vehicle. The mission design calls for SIM to be placed in an Earth-trailing orbit similar to that of the Space Infrared Telescope Facility (SIRTF). Such an orbit has the system orbiting the Sun at 1 AU but falling increasingly behind the orbit of Earth as the mission proceeds. This will provide an extremely stable thermal environment for the instrument while maintaining sufficient communication rates. Each of SIM's four interferometers consists of two 35-cm aperture telescopes that compress the starlight beams down to

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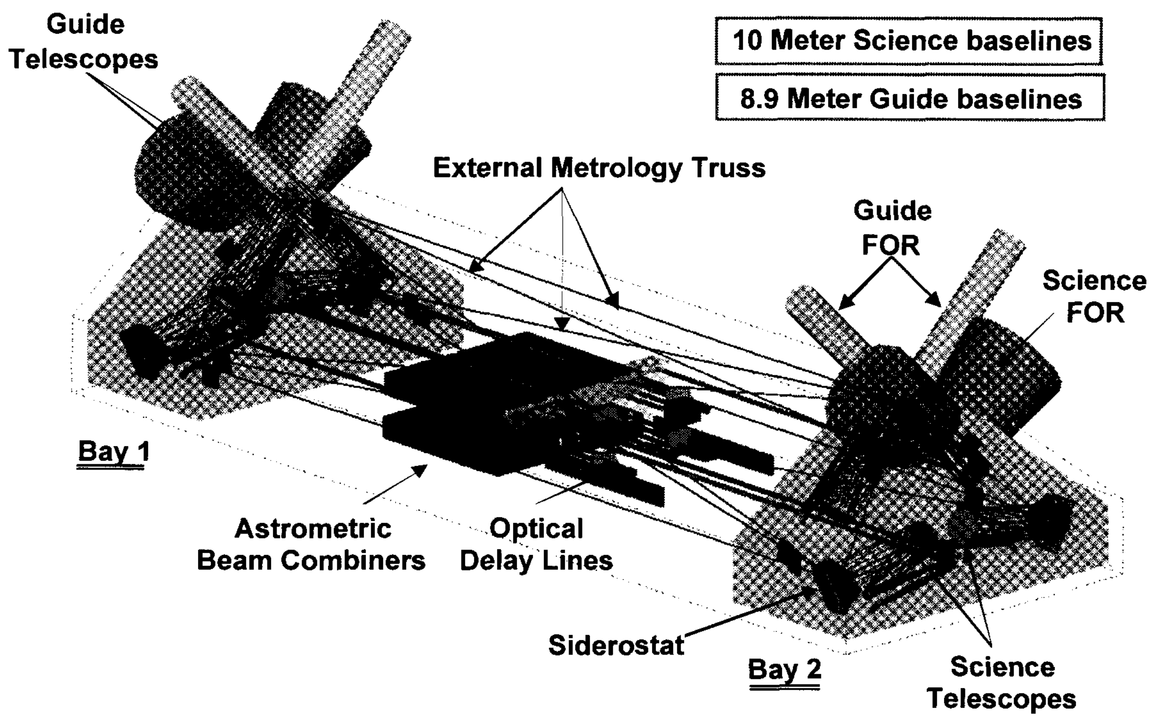

Fig. 2: SIM interferometer instrument.

about 3 cm and route the light through beam trains to the beam combiner where stellar interference fringes are formed. The telescopes of the two guide interferometers are pointed directly at guide stars, which are used to provide precise inertial reference for the instrument. The telescopes of the two science interferometers (only one is operational at a given time) are fixed to the precision structure but each one has a steering flat in front of it which can pick out stars over a 15-degree conical field of regard (FOR). These steering flats are called "siderostats." The guide telescopes and science telescopes along with the science siderostats are packaged together at each end of the structure in "Bays" 1 and 2. The guide telescopes and science siderostats are optically connected to one another by an "external metrology truss" whose 15 laser beams query corner cubes located in the centers of the siderostats and immediately in front of the guide telescopes. This allows the external metrology to determine the relative orientation of the interferometer baselines to sub-nanometer precision.

2. MAJOR TECHNICAL CHALLENGES

This paper proceeds by discussing the key technical challenges faced by SIM and the technology development approach to meet them. As an overview paper, there is appended an extensive list of references which contain greater technical detail on the various elements of interferometry technology. A short digression on how SIM makes astrometry measurements is necessary to motivate the enabling technology.

Let's start by considering a simplified layout of a single generic interferometer depicted in Fig. 3. Think of this as SIM's science interferometer and ignore the fact that telescopes

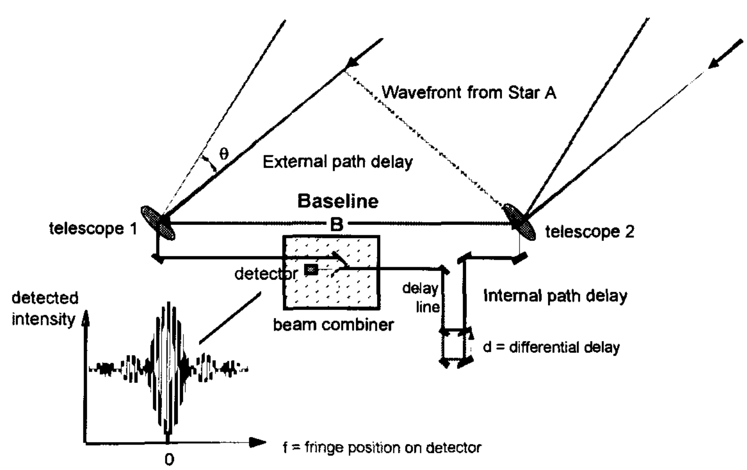

Fig. 3: Measuring the angle between two stars.

are shown as directly receiving the starlight rather than siderostats. Starlight from a "Star A" is collected by both "telescope 1" and "telescope 2" and is combined at the interferometer's "beam combiner" where a fringe pattern is imaged on the "detector." A fringe pattern will appear on the detector only if the total distance traversed by stellar photons from the star through each arm of the interferometer is equal (to within a few microns). In order to equalize the stellar pathlengths the "delay line" must be positioned such that an amount of "internal path delay" is added to arm 2 of the interferometer to offset the "external path delay" experienced by arm 1. Now imagine that the interferometer baseline "B" is sitting absolutely still in inertial space. In order to measure the angle, θ, between Star A and another star (call it Star B), the interferometer's telescopes are slewed from Star A to acquire Star B and the delay line is repositioned by a distance "d" (called the differential delay) such that the stellar fringe for Star B appears on the detector. Now the angle θ can be determined by measuring the differential delay and, to first order, dividing it by the baseline length B. How do we measure the differential delay? We do so with a laser metrology gauge that constantly samples changes in the path lengths internal to the interferometer by launching laser beams from the beam combiner through both arms of the interferometer out to corner cubes in front of the two telescopes (or on the siderostats as the case may be). The beams return from the corner cubes and, having hit all optical surfaces internal to the interferometer, allow the "internal" metrology gauge to monitor the differential delay. So, an interferometer does astrometry by measuring the differential delays between a field of stars. By observing star field after star field, the positions of stars over the entire sky can be mapped. The accuracy of the star map is directly proportional to the accuracy of the differential delay measurements. SIM, for its planet finding science, aims to measure angles between stars to an accuracy of 1 microarcsecond (5 picoradians). Hence, the requirement on internal metrology is to measure differential delays to order of 50 picometers. Two additional requirements emerge by reference to Fig. 3: (i) the position of the stellar fringe on the detector must also be read out to an accuracy of order 50 picometers; (ii) the stellar fringe must be stable on the detector at about the 10-nanometer level in order to provide a crisp "high visibility" fringe that can be read with the accuracy just mentioned.

One problem left to be resolved from the discussion above is the assumption that the science interferometer baseline B is sitting absolutely still in inertial space. In reality it will be moving at the level that the attitude control system (ACS) of the spacecraft allows. SIM will use a standard ACS that will control the interferometer to a stability of about 1 arcsecond, a mere one million times larger than the star angle error requirement. So we will need a means of providing knowledge of the attitude of the science baseline at the microarcsecond level as it wanders around. This knowledge is provided by SIM's two "guide interferometers" working in concert with the "external metrology" truss (see Fig. 4). The figure shows six corner cubes (the spherical balls that delineate a roughly 10m x 2m x 2m triangular prism) connected pairwise by 15 metrology beams forming the external metrology truss. Each of the 15 legs of the external metrology truss consists of a metrology gauge very similar to the internal metrology gauge described above. The two corner cubes at the top of the figure sit in front of the four telescopes that comprise the two guide interferometers. Another way of saying this is that the two, guide interferometers share a common baseline called out as the "guide baseline" in the figure. The "science baseline" is shown in the foreground of the figure and is delineated by the two corner cubes that sit on the science siderostats. The third baseline in Fig. 4, delineated by the two corner cubes in the background, is a second science baseline for operational redundancy. The attitude motion of the science baseline is tracked as follows: (i) the guide interferometers track the motion of the guide baseline by maintaining lock on bright guide star stellar fringes while monitoring the guide interferometer internal metrology gauges; (ii) the external metrology truss transfers the attitude of the guide baseline to the science baseline. All of this, of course, needs to be done with microarcsecond precision, leading to the requirement that the metrology gauges of the external metrology truss make measurements with picometer regime errors, similar to the requirements on the internal metrology gauges.

Hence, successful development of SIM requires that two grand technological challenges be met and overcome:

(1) picometer level sensing of stellar fringe position and optical element relative positions over meters of separation distance
(2) nanometer level control and stabilization of optical elements on a lightweight flexible structure

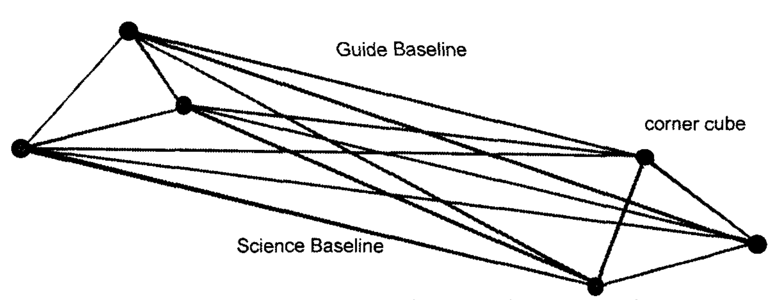

Fig. 4: Maintaining microarcsecond knowledge of the motion of the science baseline.

A third significant technical challenge has to do with overall instrument complexity and the implications for interferometer integration and test and autonomous on-orbit operation.

The complexity of an interferometer, with all its moving parts and control systems, is the price that must be paid for stepping beyond the paradigm of rigid monolithic telescopes as built since the days of Galileo. SIM will have to use active feedback control for at least 50 optical degrees of freedom. Another roughly 50 degrees of freedom will need to be controlled in open loop fashion. Additional degrees of freedom will require articulation at least once for initial deployment and instrument alignment. All of this places great importance on the development of realtime software capable of autonomously operating SIM. New and creative integration and test methods will also be required to enable development of the instrument at an affordable cost.

3. TECHNOLOGY DEVELOPMENT APPROACH

Fundamentally the approach taken to technology development is one of rapid prototyping of critical hardware and software followed by integration into technology testbeds where critical interfaces can be validated, system level performance demonstrated, and integration and test procedures developed and verified. To some extent, due to the objective of completing the technology development by the end of 2004, this will entail concurrent engineering (e.g., we will need to develop some hardware component brassboards in parallel with the development of the testbeds, dictating that breadboards of those components will be used in the testbeds rather than brassboards, which would be preferred).

This approach places the ground testbeds at the very heart of the technology development effort. It is in these testbeds that the technology products will be validated and technology readiness demonstrated. It is also in these testbeds that our engineering team will learn about what works and what does not when it comes to integrating and testing interferometers.

3.1 Component Hardware Development

Breadboards and brassboards of the new technology components required by SIM will be built and tested by the technology program. The objectives arethreefold: mitigate technical, schedule, and cost risk associated with key hardware components early in the SIM project life cycle (when the cost of correcting problems is low); deliver necessary components to the technology integration testbeds; transition the capability to manufacture the components to industry.

Over the past year the project has completed demonstrations of the last key pieces of breadboard component technology. These are laser metrology with relative motion accuracies less than 50 pm and white light fringe sensors with less than 30 pm error.

A laser metrology gauge consists of a beam launcher interposed between two corner cubes whose relative motion is to be measured. The beam launcher has a detector capable of sensing minute changes in the phase of the laser beam that interrogates the two corner cubes. Fig. 5 shows a photo of a prototype beam launcher. It is built mostly out of zerodur parts since thermal stability is very important. Test data indicates that we have succeeded in building a laser gauge with less than 100 pm of error over microns of corner cube motion (Fig. 6) and with thermal stability of less than 8 pm/mK of bulk temperature change (Fig. 7). Both of these performance parameters are within a factor of 2–4 of ultimate flight requirements indicating that the basic technology is essentially in hand.

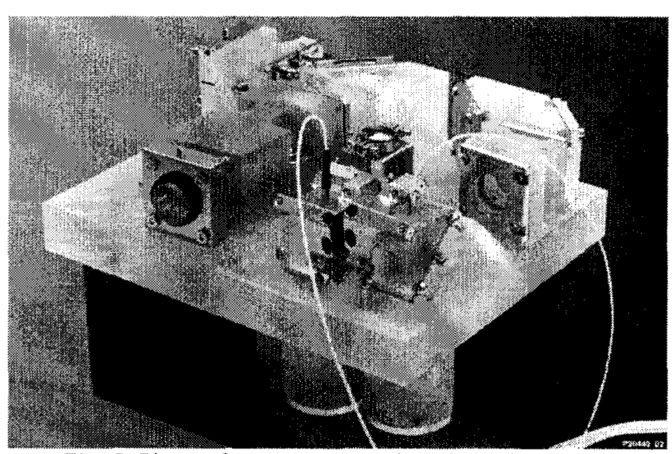
Fig. 5: Photo of prototype metrology beam launcher.

The "white light experiment" has recently demonstrated the ability to measure broadband fringe positions to less than 30 pm. Fig. 8 shows a layout of the white light experiment. White light is fed into the beam combiner, propagates backward through the beam combiner and delay line and is retro-reflected by the fast steering mirror back to the CCD camera fringe detector. Fringe estimates are made by monitoring the fringe intensity pattern while modulating the optical path approximately one wave using the PZT stage of the delay line. A He-Ne laser is simultaneously injected into the white light fiber and is used as a truth reference for the fringe position. Fig. 9 shows an Allan Variance curve (bounded by 90% confidence error bar curves) of the difference between the phase estimate from the white light fringe detector and the He-Ne laser signal. At the 30 second integration time planned for SIM, fringe read error is about 22 pm, beating the flight requirement with margin. This is a huge step forward for the SIM technology development effort.

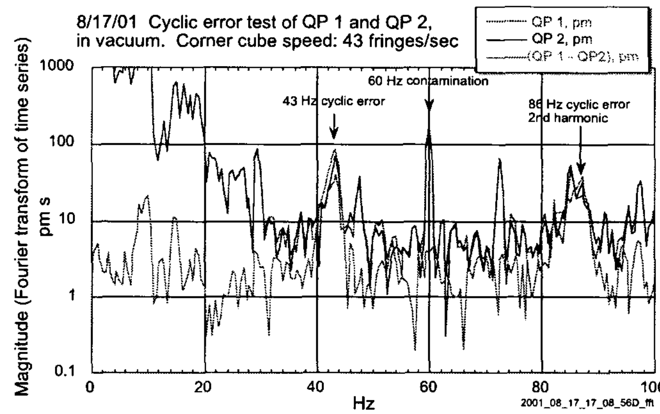

Fig. 6: Gauge performance of under 100 pm over micron regime corner cube excursions.

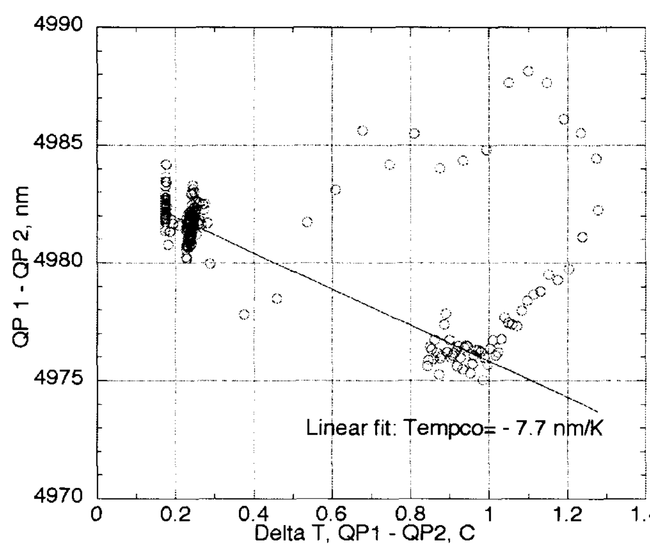

Fig. 7: Gauge performance of under 8 pm/mK thermal sensitivity to 1 Kelvin class temperature excursion.

Most of the components on which technology performance demonstrations have been done have been breadboards rather that brassboards. Only those components considered as high risk will be built and tested as brassboards (near flight form, fit, function). Figure 10 depicts the brassboard optical delay line that has finished development, performance and environmental testing.

3.2 Prototype Realtime Software Development

Space interferometers will be required to operate with limited intervention from the ground and in doing so perform initial optical alignment, calibration, stellar target acquisition, angle tracking, fringe tracking, slew, continuous rotation for synthesis imaging, and other autonomous functions. Realtime software will play the central role in performing these functions. This software represents a significant technical challenge since it will have to operate a very complex instrument, run on a distributed set of computers, and control processes at timescales from milliseconds to days. As advanced systems demand increasingly sophisticated software, the portion of project cost (and associated schedule and cost risk) assigned to software begins to rival that of hardware. Hence, the technology program has determined to place the importance of the development of realtime software on a par with that of interferometer hardware.

The development of SIM prototype software takes place in a development environment called the Realtime Interferometer Control Software Testbed (RICST). RICST builds the code in a modular fashion and is making a series of incremental deliveries. This greatly simplifies the process of testing and debugging. The initial deliveries were internal to the RICST team and served to validate the development approach and train the personnel. RICST testing incorporates breadboard and brassboard hardware allowing the software to be fully exercised by actually driving the relevant controlled components. RICST software is being incrementally delivered to integration testbeds (described below) where it is being used to operate complete interferometers like SIM. This process is expected to result in software that is mature enough to form a solid springboard for the development of flight code.

3.3 Integrated Modeling Tool Development

The challenges facing space interferometry do not lie exclusively in the province of developing component hardware and realtime control software. Work is also needed to advance the state-of-the-art for software tools for analysis and design. Existing analysis tools provide only limited capability for evaluation of spaceborne optical system designs. They determine optical performance from the geometry and material properties of the optical elements in the system,

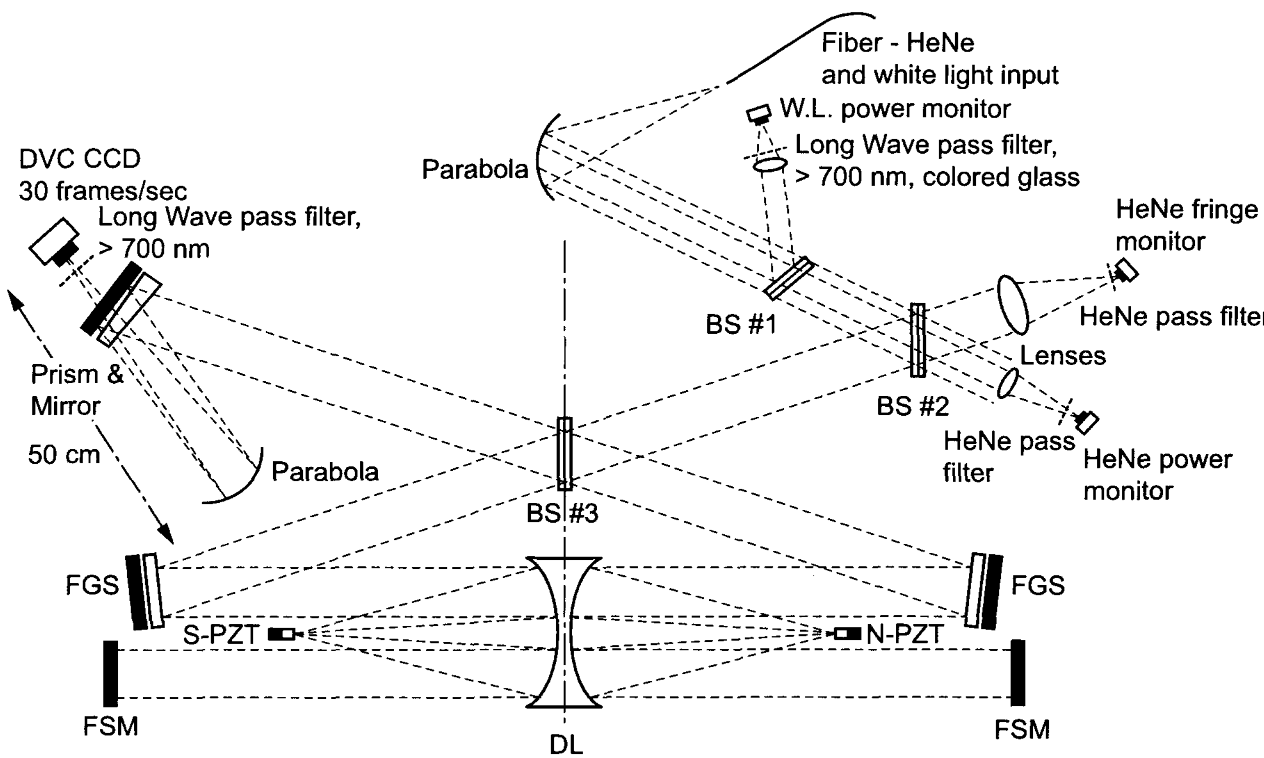

Fig. 8: Layout of white light fringe detection experiment.

assuming only minor deviations from the nominal alignment and figure. They cannot evaluate the impact on optical performance from controlled/articulated optics, structural dynamics, and thermal response, which are important considerations for future interferometer missions. To investigate these critical relationships, a new analysis tool has been developed called Integrated Modeling of Advanced Optical Systems (IMOS). IMOS enables end-to-end modeling of complex optomechanical systems (including optics, controls, structural dynamics, and thermal analysis) in a single seat workstation computing environment. IMOS has been applied at JPL to the Hubble Space Telescope and the Space Infrared Telescope Facility (SIRTF), as well as virtually all the space interferometer designs that have been considered in recent years (e.g., SIM, OSI, ISIS, SONATA, DLI, FMI, MPI, POINTS).

IMOS was originally created as a modeling tool to assist in the early design phases of multidisciplinary systems. In recent years IMOS has matured tremendously and has greatly increased its ability to address complex, many degree-of-freedom systems that are typical of the detail design phase. Currently IMOS is the baselined integrated modeling tool for the SIM project and NGST pre-project, and is also being adopted by their industrial partners. Fig. 11 shows a thermal/mechanical analysis run in IMOS predicting the deformation of one of SIM's collector telescopes over expected temperature changes.

3.4 Ground Integration Testbeds

Optical interferometry is not yet sufficiently mature to allow us to assure system performance on the basis of an exhaustive set of component tests. Rather it is necessary at this point to do validation testing at higher levels of integration to prove the technology is ready. This is the province of the ground testbeds.

Three major ground testbeds are planned: the evolutionary SIM System Testbed (STB-1,3), the Microarcsecond Metrology (MAM) Testbed, and the Kite Testbed. This particular delineation of the ground testbed effort derives from the recognition that one major subset of the technologies can be tested in air at nanometer precision and at full scale while another subset must be tested in vacuum at picometer precision but at subscale. The first set of technologies, i.e., those associated with vibration attenuation, is grouped into the STB. The second, i.e., the laser metrology technologies, is assigned to the MAM and Kite Testbeds.

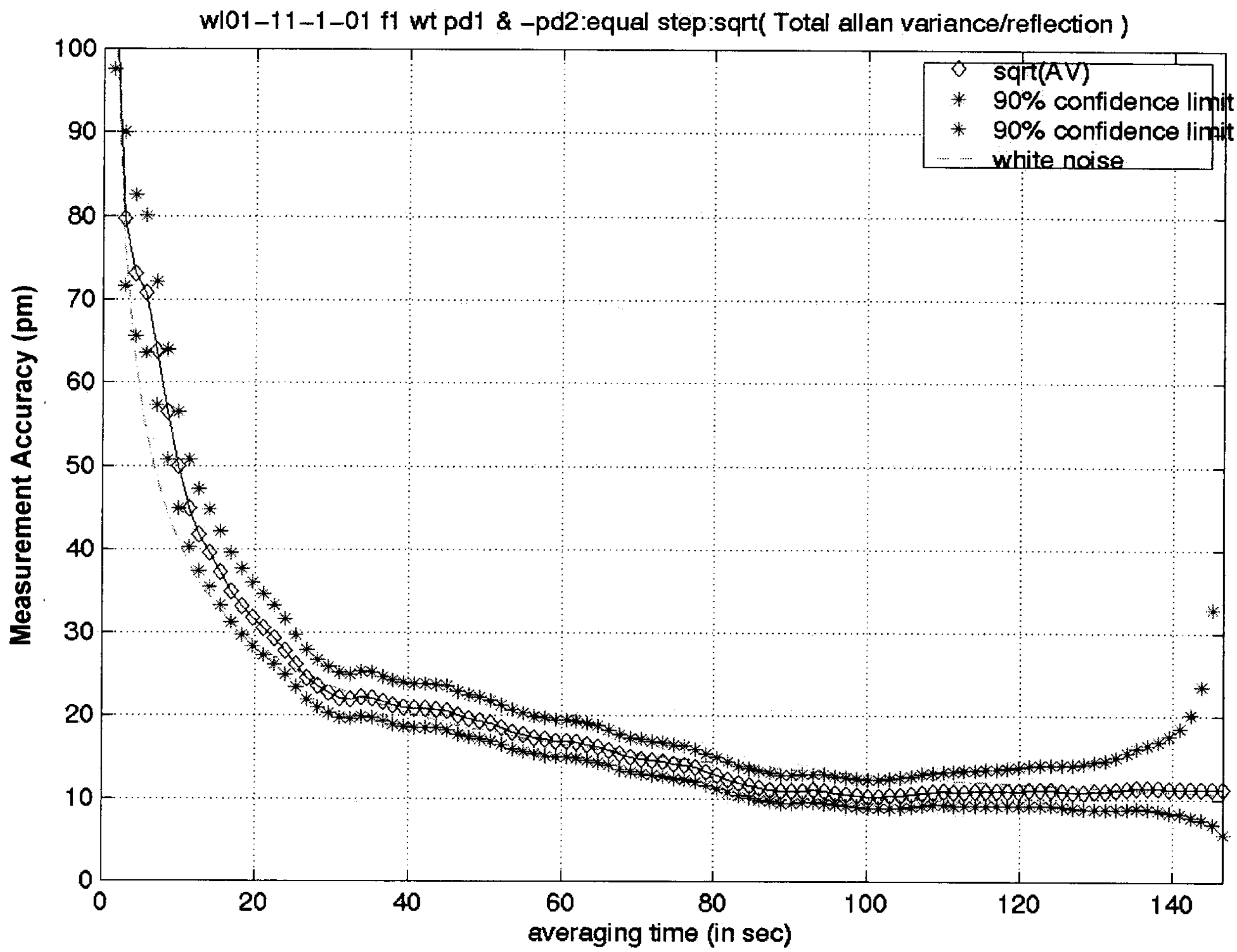

Fig. 9: Allan variance of consistency between white light fringe readout and HeNe laser gauge.

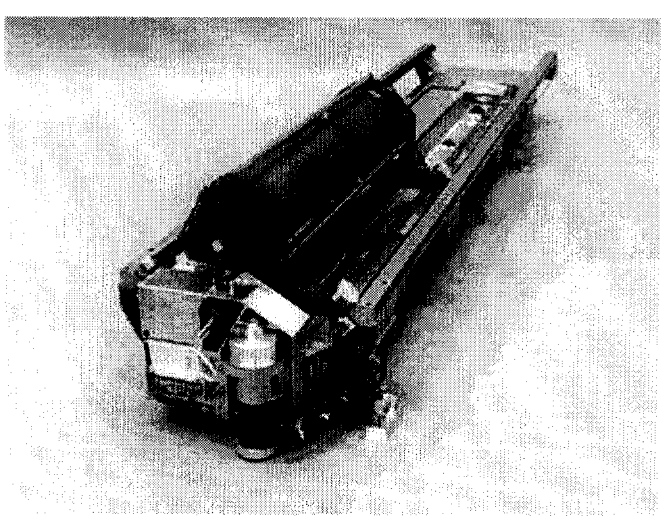

Fig. 10: Brassboard optical delay line.

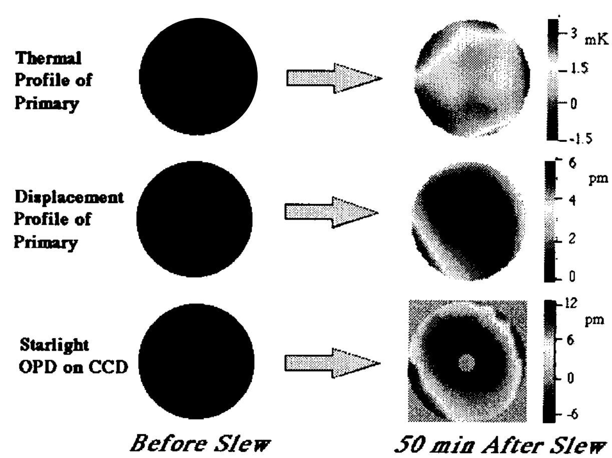

Fig. 11: Collector deformation map over temperature.

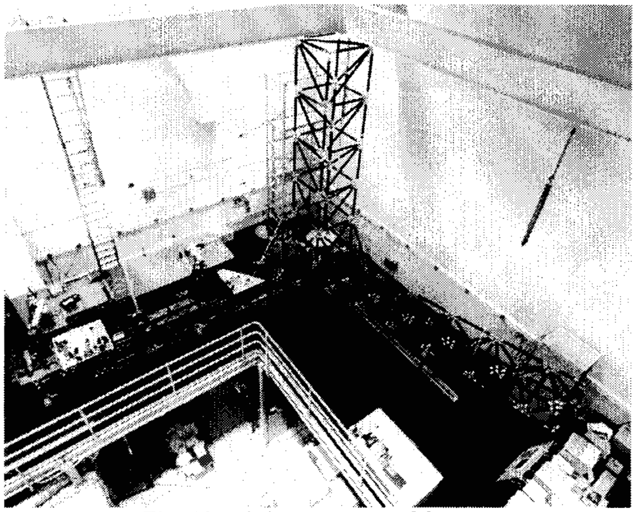

Fig. 12: Bird's eye view of STB-1.

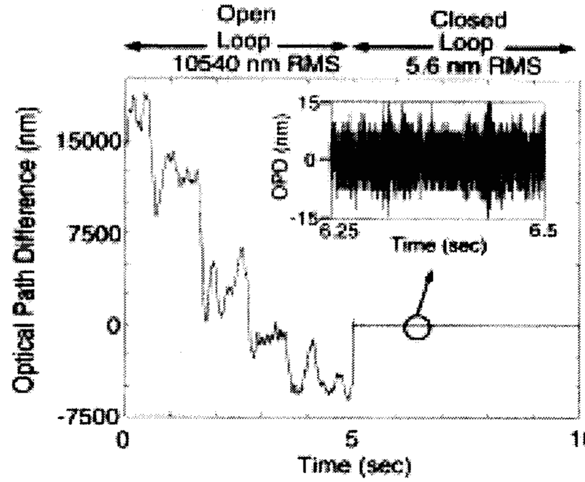

Fig. 13: Time trace of STB-1 fringe tracking OPD with control loops open/closed.

The structure is a 7m × 6.8m × 5.5m aluminum truss weighing 200 kg (with optics and control systems attached the weight is about 600 kg). Three active gravity off-load devices make up the structure's suspension system providing about a factor of ten separation between the structure's "rigid body" and flexible body modes (the lowest of which is at about 6 Hz). The equipment complement includes a three tier optical delay line with associated laser metrology, a pointing system complete with two gimballed siderostats, two fast steering mirrors, and coarse and fine angle tracking detectors, a six-axis isolation system, and all associated electronics and real time computer control hardware necessary for closed loop system control and data acquisition. The principal objectives of STB-1 are demonstrating vibration attenuation technologies and validating the IMOS modeling tool in the nanometer regime. STB-1 was completed during the summer of 1994 when "first fringes" were acquired. Two metrics have been tracked over time to monitor testbed progress. These are: (a) pseudo-star fringe tracking stability in the presence of the laboratory ambient vibration environment and; (b) fringe stability vs. emulated spacecraft reaction wheel disturbances, which are expected to be the dominant on-orbit disturbance source. The current performance, as measured by each metric, is below 5 nm RMS (see Fig. 13 for a typical lab ambient fringe tracking time trace).

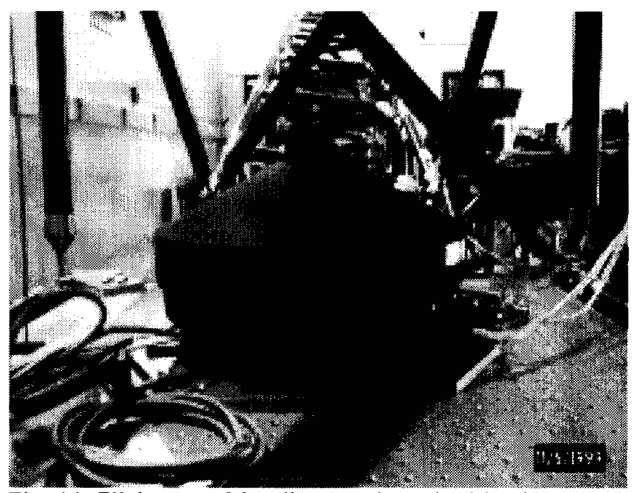

Fig. 14: Flight spare Magellan reaction wheel hard mounted on STB-1.

Recent experiments have been conducted utilizing a flight spare reaction wheel as the disturbance source rather than using a shaker. Fig. 14 shows the wheel mounted on the structure. The motivation is to verify that we can accurately predict the response to an actual wheel, which, with its internal compliance and mass distribution, is a more complex mechanical device than a shaker. Fig. 15 shows a comparison between the

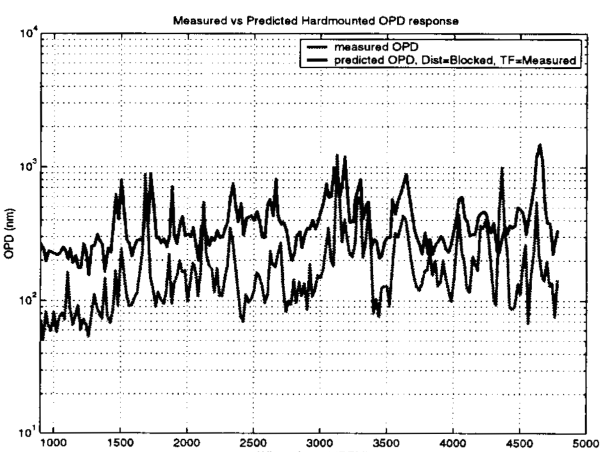

Fig. 15: Wheel response; predict vs measurement.

predicted response (darker trace) with the measured response (lighter trace) as a function of wheel speed. Notice that the prediction nicely over bounds the measurement by about a factor of two at most wheel speeds, lending confidence that our predictive capabilities are both accurate and conservative. Note also that the high levels of response (hundreds of nanometers) are due to the facts that (i) the wheel is much noisier than the ones intended for use on SIM, and (ii) the data was taken with the wheel in the hard mounted configuration.

As the name implies, STB-3 is a three-baseline testbed. Its objectives are twofold: (1) to demonstrate that information from the guide interferometers and the metrology system can be fed at high bandwidth to the science interferometer enabling it to track, in angle and phase, dim science stars; (2) to demonstrate the capability to integrate and operate a system of comparable complexity to the flight instrument, thereby serving as a pathfinder for the flight system integration and test.

The STB-3 approach is to proceed in two phases. In Phase 1, we will develop dim star phase tracking on optical tables, which entails three-baseline "pathlength feedforward." Phase 2 moves the three interferometers onto a SIM-scale flexible structure and repeats the dim star tracking experiments, demonstrating rejection of disturbances at the levels required by SIM.

The testbed is currently conducting Phase 1 testing on optical tables (Fig. 16). We are tracking fringes on all three interferometers and are stabilizing dim star fringes at near flight levels in the face of simulated spacecraft attitude motions of the table. Figs. 17 and 18 show, respectively in the time and frequency domains, the level of attenuation achieved so far. The 80 dB rejection represents a factor of 10,000 and is essentially at the level of performance required of the flight system. By late 2002 we plan to relocate the optics to the 9-meter flexible structure shown in Fig. 19 and begin vibration attenuation testing.

Microarcsecond Metrology (MAM) Testbed—The sub-nanometer and microarcsecond measurement technology needed by SIM will be demonstrated through two major testbeds, MAM and Kite, which are closing in on important performance milestones. MAM is a single baseline white light interferometer fed by a reverse interferometer pseudostar and is currently operational at JPL (see Fig. 20).

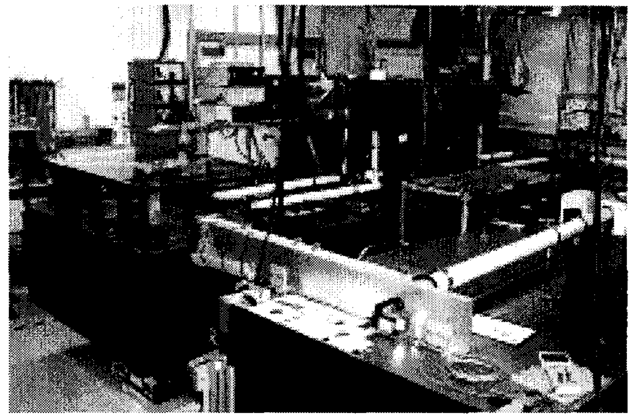

Fig. 16: STB-3 on optical tables.

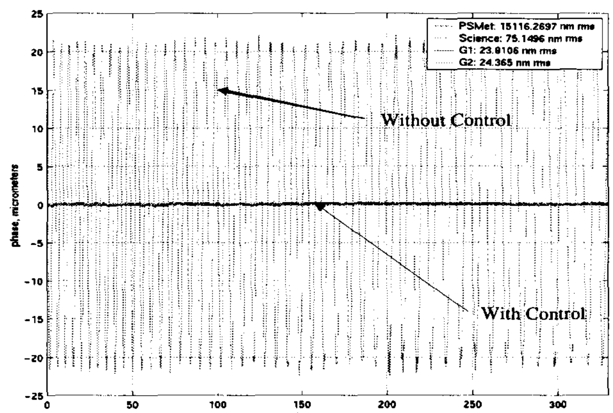

Fig. 17: Time domain dim star tracking data.

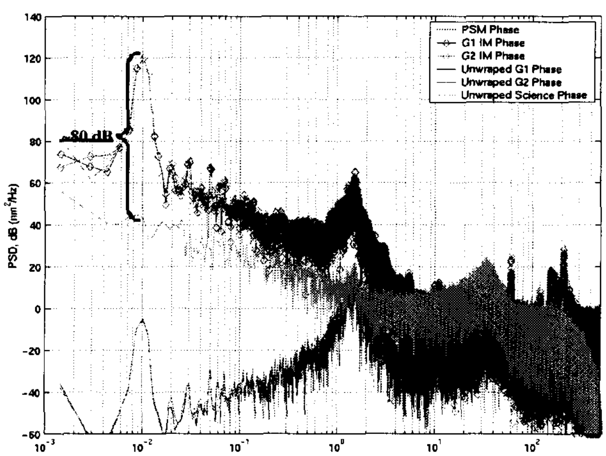

Fig. 18: Frequency domain dim star tracking data.

MAM's single interferometer includes siderostats for wide-angle acquisition, fast steering mirrors for high precision pointing, a delay line to control optical path and a beam combiner with both pointing and pathlength sensors. Additionally, internal metrology beams integrated into the beam combiner are used to measure the optical path between

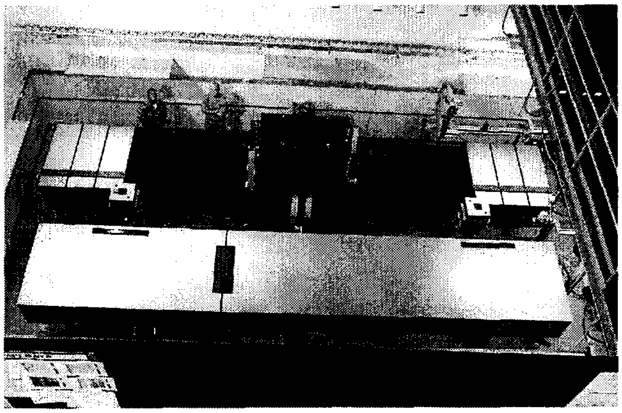

Fig. 19: STB-3 structure (shown upper portion of photo) installed in laboratory high bay.

the combiner and each arm of the interferometer. An inverse interferometer pseudostar (IIPS) is used to feed white light into the MAM interferometer (see photo in Fig. 21). The IIPS also uses internal metrology beams that monitor the optical path from its main beamsplitter to the fiducials on the MAM interferometer. By comparing the white light fringe measurement and the metrology measurements from both the interferometer and the pseudostar as the angle of the "star" is varied, one can measure optical path measurement errors arising from a number of sources that are present on SIM. These include diffraction effects from moving delay lines, surface figure errors in the interferometer optics, and fringe estimation errors.

Both the MAM interferometer and IIPS have been placed in a vibration-isolated, thermally stabilized vacuum chamber large enough to accommodate the 2-meter scale interferometric baselines. Doing so eliminates optical path errors due to fluctuations in the refractive index of air. To date, performance data has been taken with the MAM interferometer and IIPS held static to establish the noise limited performance of the testbed. Fig. 22 shows MAM static (also known as field independent) performance as a function of observation time. Times longer than 30 sec allow the data to be "chopped" or differenced, which removes the effects of slow drift errors. The performance in the figure meets our initial goals for field independent errors. Field dependent testing, with both the IIPS and the test article optics moving, is now under way.

Kite Testbed—Kite is aimed at demonstrating that the laser metrology gauges discussed above can be built up into multiple gauge configurations capable of measuring the relative motion of optical fiducials (viz., corner cubes) in more than one dimension. Such a multiple gauge configuration is referred to as an "optical truss." On SIM a three dimensional optical truss consisting of 15 gauges is used to monitor the relative motion of the

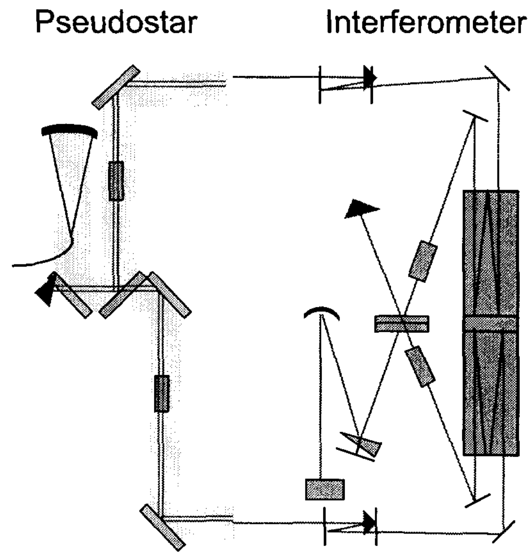

Fig. 20: Schematic of MAM interferometer and pseudostar.

Fig. 21: MAM inverse interferometer pseudostar (IIPS) in final assembly.

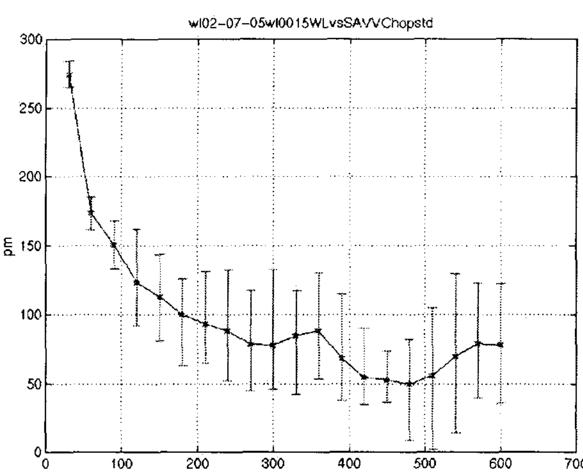

Fig. 22: MAM field independent performance data.

corner cubes located on the system's main starlight receiving optics. The testbed that will demonstrate the optical truss concept is called Kite for reasons that become obvious when one looks at the configuration depicted in Fig. 23. Kite consists of 6 laser gauges in a plane laid out to resemble a kite. The call outs in the figure are the passive corner cube (PCC), the active corner cube (ACC), two triple corner cubes (TCC) and 6 so-called "quick prototype" or QP beam launchers of the type pictured in Fig. 5. The primary experiment is to articulate the ACC in x, y, and tip/tilt over about 10 microns and ±7.5° and to measure that motion with the 6-gauge optical truss to about the 100 pm level. Six gauges in a plane is the smallest number of gauges that allow for a multi-dimensional consistency test. That is to say, that the outputs of any of five gauges is sufficient to predict the output of the sixth gauge. If these quantities agree to 100 pm, then the program will declare success on the optical truss technology and move toward a test of a three dimensional optical truss in conjunction with the build of the flight system.

Kite is currently fully operational and installed in its vacuum chamber (Fig. 24). Similar to MAM, it is about done taking static performance data. Fig. 25 shows the optical path length outputs of the 6 laser gauges during a recent long duration data run. Note that even without commanding any corner cube motion the gauges track motions on the order of 0.5 micron as the experiment responds to temperature variations in the chamber. When the testbed consistency metric is computed the result is the time trace in Fig. 26. Note that even though the corner cubes are drifting on the order of a micron (Fig. 25), the Kite optical truss is able to make realtime measurements of this motion that are good to under 20 nanometers RMS. And, once this "raw" data is processed in a SIM-like manner using 10 thirty-second chops (similar to the MAM chopping data of Fig. 22), the static (viz., field independent) performance is as shown in Fig. 27. Kite is also now pursuing the field dependent testing that will be the ultimate measure of optical truss technology development.

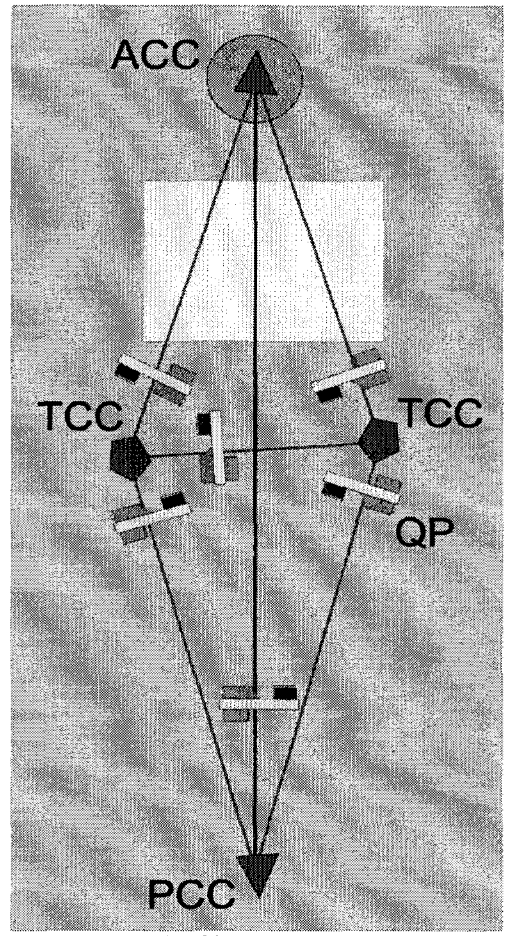

Fig. 23: Kite layout.

Subsystem Testbeds—In addition to the major system level testbeds, a number of testbeds are planned to focus more sharply on demonstrating particular capabilities better tested at lesser degrees of integration. The Thermal Opto-mechanical (TOM) Testbed is an example. TOM, under the direction of Lockheed-Martin's Palo Alto Advanced

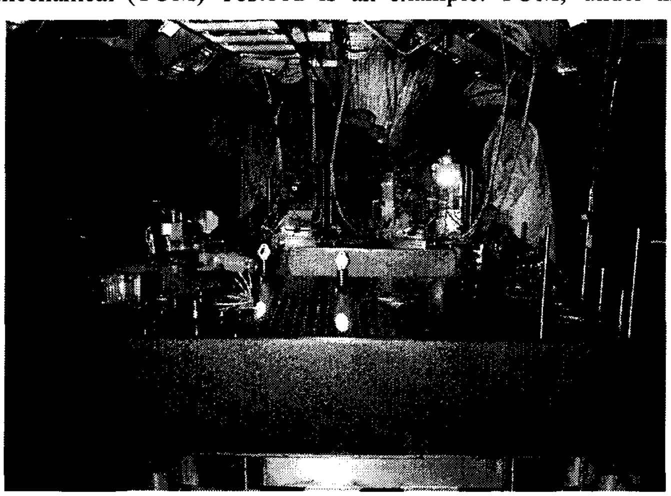
Fig. 24: Kite testbed in vacuum chamber.

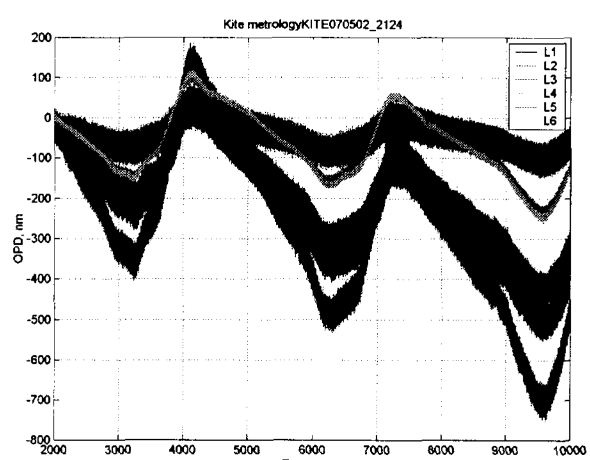

Fig. 25: 6-gauge output.

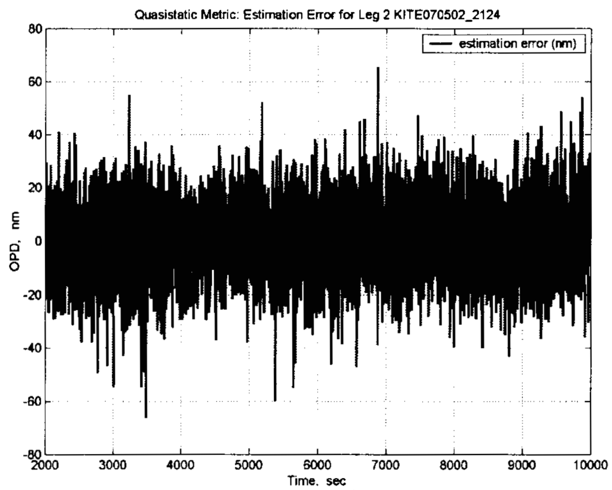

Fig. 26: Kite metric output.

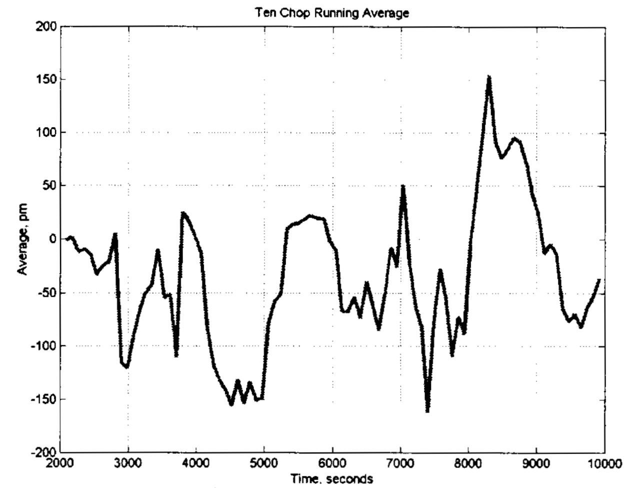

Fig. 27: Kite field independent performance data.

Technology Center, is aimed at exploring the response of optical figure to small changes in thermal conditions. This is a critical area for SIM. Since the SIM metrology system samples only a small portion of each collecting aperture, sub-nanometer changes to optical figure across the apertures during the course of an observation would result in misleading estimates of the optical path excursions seen by starlight. SIM's design solution is to maintain very tight (< 10 mK) thermal control of time varying gradients across the collecting optics. Thermal-optical-mechanical modeling indicates that these small mirror temperature excursions will insure acceptably small distortions in optical figure. The TOM Testbed's job is to prove that this is the case.

TOM will proceed in three major steps. Test #1 has been completed. This is a thermal-only experiment where a 33 cm Pyrex mirror (Fig. 28) in a thermal vacuum tank is exposed to time varying thermal loads and its temperature response is recorded. These data are compared to predictive thermal models. Test #2 introduces optical figure measurement so that mirror temperature changes can be experimentally correlated with changes in figure. Test #2 uses a relatively high CTE test optic so that mechanical response will be exaggerated (compared to SIM) leading to high SNR measurements and easier model comparison. Test #3 introduces a flight-traceable low-CTE telescope as the test optic and a test environment closely emulating on-orbit conditions.

Test #1 objectives were to verify temperature sensor performance and thermal modeling capability in the mK regime. Both objectives were met in impressive fashion. The temperature sensors, platinum resist thermometers (PRTs), were shown capable of sub mK resolution. The thermal modeling predicted temporal changes in through-mirror temperature gradients to an accuracy of about 20% (Fig. 29). This is critical to SIM since it is the through-mirror gradients that are expected to produce the majority of mirror deformation. This postulate will be examined in Test #2.

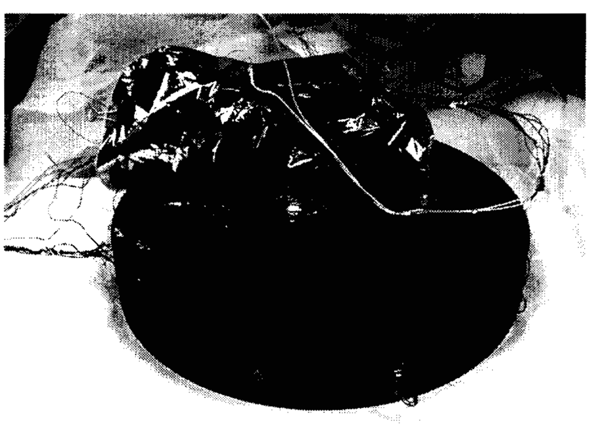

Fig. 28: Pyrex mirror for TOM Test #1.

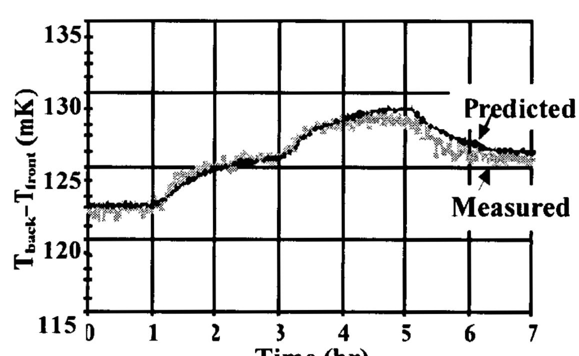

Fig. 29: Time Variation of TOM Mirror Front-to-Back Thermal Gradient—Actual vs Predict.

4. SUMMARY

Scientifically, SIM will open new vistas, including the discovery of Earth mass planets in our galactic neighborhood. However, the technology necessary to make SIM a reality presents unprecedented challenges in the fields of nanometer stabilization, picometer sensing, and complex system integration, test, and autonomous operation. However, we are far from starting from scratch on this development effort. Work on these technologies has been underway for almost 20 years. As exemplified by the sub 100 pm results on laser metrology gauges and "stellar" fringe sensors, the component technologies for SIM are essentially in hand. What remain outstanding are critical demonstrations at the subsystem and system level. These are also proceeding nicely. With these completed by 2004 SIM will be ready to begin flight system development with its formidable technical risks well understood and its critical technology in hand.

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